An upper limb myocontrolled neuroprosthesis to enhance rehabilitation outcomes of neurological patients

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1 Introduction

The combination of functional electrical stimulation (FES) with externally powered exoskeletons has become a promising technique able to blend together the strengths of each technology so as to improve the rehabilitation outcomes of neurological patients suffering from arm weakness [4]. A good compromise is to exploit a passive exoskeleton equipped with controlled brakes and passive springs for weight relief with FES systems which modulate the timing and intensity of the stimulation on the basis of the residual volitional activity of the subject. Myocontrolled FES systems augment the force produced by weak muscles and assure the patient's involvement during training. The exoskeleton can instead provide the weight relief to facilitate the movement and avoid the use of FES to hold predefined positions, thus reducing muscle fatigue [2]. These complementary characteristics make this methodology potentially effective in promoting motor re-learning of functional skills.

This study aims at showing the feasibility of the two different myocontrolled FES systems for arm rehabilitation. Both systems will be extensively validated both in clinical and home settings during the just started European project RETRAINER (www.retrainer.eu).

2 Materials and Methods

The apparatus and the two EMG-based control strategies for FES are described. Both strategies can be theoretically applied to any arm muscle based on the individual needs.

2.1 Apparatus

It consists of a passive arm exoskeleton (Fig. 1), a current-controlled stimulator (Rehastim™, HASOMED) delivering 25-Hz biphasic stimuli, a multi-channel EMG amplifier (Porti 32™, TMS International), and a PC running Scilab/Scicos under RTAI-Linux.

The exoskeleton weights 2.2kg and has 3 degrees of freedom (DOF) measured by encoders: shoulder elevation in the sagittal plane, shoulder rotation in the horizontal plane, and elbow flexion/extension [1]. A spring mechanism to provide a manual adjustable weight support is included in the mechanical shoulder joint. Electromagnetic DC brakes can lock each DOF.

Separate electrodes for stimulation and EMG recordings are placed on the belly of the target muscle: EMG electrodes are placed within the stimulation ones.

During hybrid muscle contractions, the overall EMG signal includes both the M-wave, i.e. the compound action potential due to synchronous firing of the FES-evoked muscle fibers, as well as the volitional EMG. Advanced EMG processing is applied to estimate both contributions: volitional EMG is estimated using the linear prediction adaptive filter proposed by [2], while the FES-induced muscle activity is calculated as the scaled 1-norm of the M-wave [3].

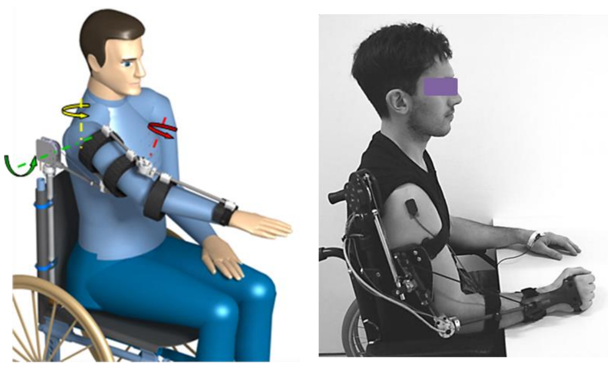

Figure 1. The 3-DOF exoskeleton arm for weight relief.

2.2 ON/OFF controller

The first control strategy is designed to allow even patients with reduced muscle contractions to autonomously activate and de-activate the stimulation support exploiting their own residual muscle activity [2].

The controller is characterized by a piece-wise linear input-output relationship (Fig. 2): when the volitional EMG exceeds the upper threshold (*ON*), the stimulation intensity (Q in the figure) linearly increases till the maximal value, Q_{max}, and then is kept constant. As soon as the volitional EMG drops below the lower threshold (*OFF*), the stimulation intensity is gradually reduced till the minimal value, Q_{min}. The two thresholds as well as Q_{min} and Q_{max} are set on each muscle and subject during an initial calibration procedure.

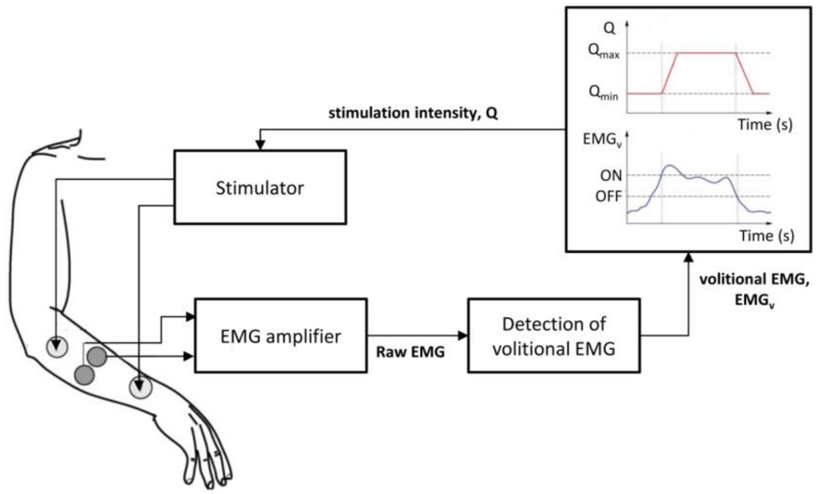

Figure 2. Control scheme of the ON/OFF controller.

2.3 Assist-as-needed controller

In the approach proposed in Section 2.2, the stimulation intensity is controlled only on the basis of the residual capability of the subject and this can lead to imprecise control of movement. The "assist-as-needed" controller is proposed to overcome this limitation. It includes an EMG-based feedback controller and a trial-to-trial adaptation of the FES angular support (Fig. 3).

The feedback controller (λ-controller in the figure) consists of a discrete-time integral controller with anti-reset-windup which regulates the relationship between the stimulation intensity q_i and the amount of FES-induced muscle activity λ_i. The reference input $\lambda_{r,i}$ of the feedback controller is derived from a pre-filter which represents the inverse of the dynamics between the FES-induced muscle activity and the angle. The input of the pre-filter is the desired FES-induced angle profile $\varphi_{s,i}$. In the absence of volitional activity the measured angle should be close to $\varphi_{s,i}$.

The trial-to-trial adaptation iteratively updates $\varphi_{s,i}$ in order to minimize the tracking error in case the subject actively contributes to the movement. To check the voluntary contribution of the subject, the volitional EMG is estimated as described in Section 2.1. If the volitional EMG is below a pre-defined threshold representing the minimal contribution requested to the subject, the FES-induced angular support is reduced to notify the subject to actively contribute.

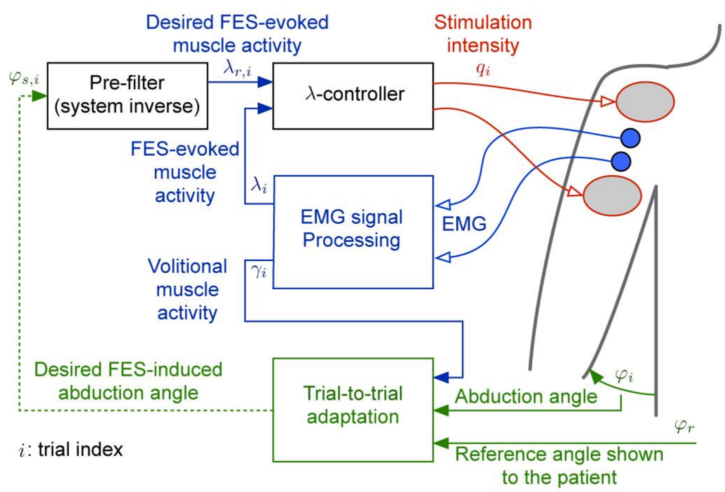

Figure 3. Control scheme of the “assist-as-needed” controller.

3 Results and Discussion

The feasibility of both control strategies were tested and exemplar results are here presented.

3.1 ON/OFF controller

A 50-year old man with incomplete Spinal Cord Injury (SCI) was asked to perform some repetitions of elbow flexion while tracking a trapezoidal angular trajectory with and without FES to the biceps brachii. All repetitions were performed with the gravity support provided by the exoskeleton. Fig. 4 shows the performance achieved: when FES was provided, the stimulation intensity was modulated in terms of pulse width (PW) using the ON/OFF controller, while the current amplitude was fixed at 10mA. It can be noticed that the PW increased when the elbow flexion started, while it was equal to zero in the resting phase between repetitions, suggesting that the subjects was able to activate and de-activate the stimulation as desired. The tracking error was reduced by 66% when FES was provided while the volitional EMG did not change. The patient understood how to control the system in a single session.

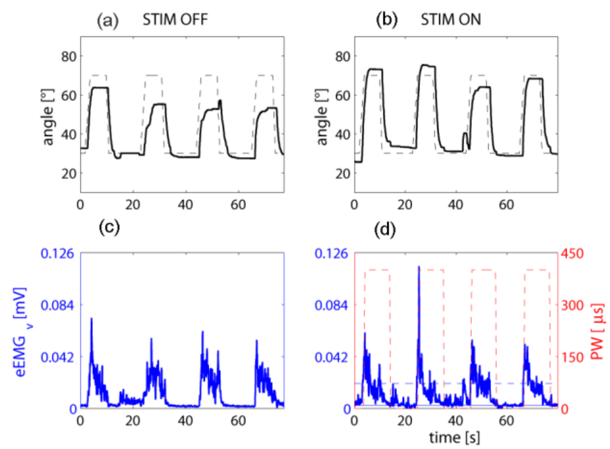

Figure 4. Tracking performance of an individual with SCI during elbow flexion without and with FES. The ON/OFF controller was used to modulate the pulse width (PW). Panels a-b: measured (solid line) and target angle (dashed line); panel c: volitional EMG; panel d: volitional EMG (blue), PW (red); ON/OFF thresholds (horizontal lines).

3.2 Assist-as-needed controller

The "assist-as-needed" controller was tested on one healthy volunteer (41-year old male). The target muscle was the medial deltoid and the stimulation intensity was modulated in terms of positive charge and, thus, both current amplitude and PW were updated. The subject performed shoulder abduction movements while tracking a trapezoidal angular trajectory and the results are shown in Fig. 5. In the first trial, he tracked the target without FES support and the maximal volitional activity was produced. In the second trial, 50% FES support was provided to the subject who did not contribute voluntarily to the movement. Thus, the angle measured (green in the upper panel) was close to the desired FES-induced angle (red), and the FES support in the following trial was reduced. During trials 2-5, the subject tracked quite well the angular trajectory and the FES support remained almost unchanged. Otherwise, during trials 9-11 a positive tracking error was computed. Since the volitional EMG was above threshold (horizontal line in the bottom panel), the FES support was increased.

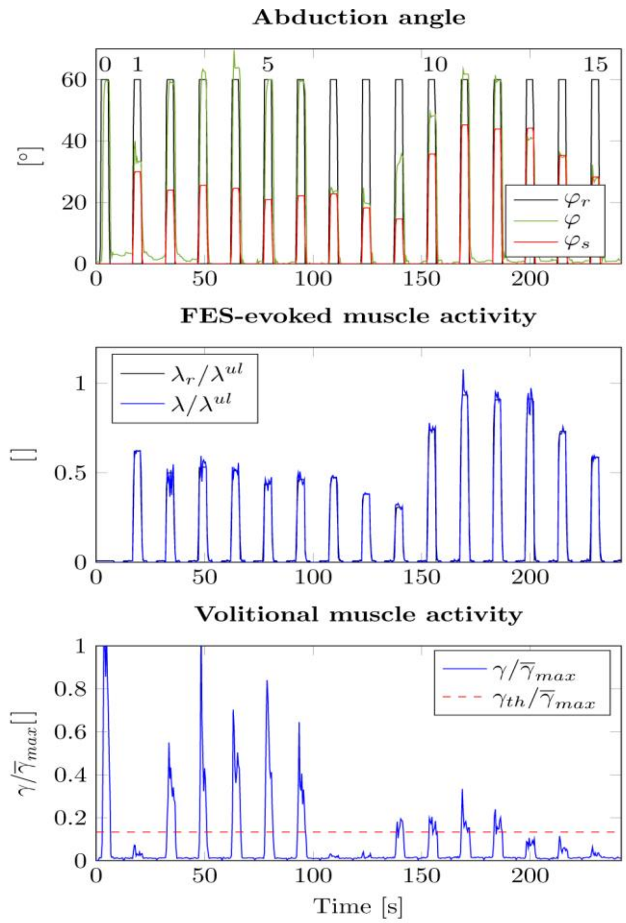

Figure 5. Performance of a healthy volunteer while using the "assist-as-needed" controller.

The controller demonstrated to work as desired on one healthy volunteer who simulated different volitional contributions of a potential patient.

4 Conclusion

Two novel myocontrolled FES systems having the potential to enhance motor relearning have been proposed. Both controllers deliver FES co-incidentally with the voluntary drive, encourage the subject's involvement in the training, and can be combined with an exoskeleton for weight relief.

The first system is easy to implement but requires the subject to preserve a certain amount of volitional activity since two different thresholds need to be identified. Furthermore, the subject can only control the timing of the stimulation but not the intensity, potentially leading to imprecise control of movement.

The second system exploits the EMG signal of the stimulated muscle to distinguish between the FES-induced angular support and the movement actually performed by the subject. The minimal FES support needed to track a given trajectory is offered to the subject who can preserve just a minimal amount of volitional EMG since a single threshold needs to be identified.

During the RETRAINER project the effectiveness of the here proposed FES systems will be evaluated in a randomized clinical study involving stroke patients.

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